# Small Second Acoustic Peak from Interacting Cold Dark Matter?

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**Abstract**

We consider a possibility to explain the observed suppression of the second acoustic peak in the anisotropy spectrum of the Cosmic Microwave Background (CMB) by interaction between a fraction of non-baryonic Cold Dark Matter (CDM) and normal baryonic matter. This scenario does not require any modifications in the standard Big Bang Nucleosynthesis (BBN). We estimate the required values of the cross-section-to-mass ratio for elastic scattering of CDM particles off baryons. In case of velocity-independent elastic scattering (in the velocity interval $v \sim 10^{-5} \div 10^{-3}$) we find that such particles do not contradict observational limits if they are heavier than $\sim 10^5$ GeV or lighter than $\sim 0.5$ GeV. Another candidate, which may appear in the models with infinite extra dimensions, is a quasistable charged particle decaying through tunneling into extra dimensions. Finally a millicharged particle with the electric charge ranging from $\sim 10^{-4}$ to $\sim 10^{-1}$ and with mass $M \sim 0.1$ GeV $\div$ 1 TeV also may be responsible for the suppression of the second acoustic peak. As a byproduct we point out that CMB measurements set new limits on the allowed parameter space for the millicharged particles.

Recently the anisotropy spectrum of the CMB has been measured with great precision resulting in the accurate determination of the shape and position of the first acoustic peak [1]. The result, being in a good agreement with the standard inflationary predictions such as adiabatic spectrum of primordial fluctuations and flat Universe, provides a strong observational support to the inflationary picture of the Early Universe.

Current data include the values of angular harmonics up to $l \sim 800$ covering the region where the second acoustic peak has been expected. In the standard inflationary $\Lambda$CDM Universe, the relative height of the first and the second acoustic peaks is governed by the fractional baryon mass density $\Omega_B h^2$ (see Ref. [2] for introduction to physics of the CMB anisotropy and further references). The latter parameter is independently determined from the primordial element abundances, $\Omega_B h^2 = 0.019$, with an accuracy of about 5% [3]. The CMB anisotropy measurements suggest somewhat higher baryon density [4],

$$\Omega_B h^2 = 0.032^{+0.005}_{-0.004} \tag{1}$$

(the upper limit here is valid assuming the prediction of simplest inflationary models that the tensor to scalar ratio is small, $r \approx 0$ [5]) which deviates from the standard BBN value at about $2\sigma$ level. New CMB measurements should reduce the uncertainty in the result (1) in the near future and thus allow to determine whether this discrepancy is real or just a statistical fluctuation.

Consequently, it is desirable to have a list of physical effects capable to modifying the CMB spectrum in the region of first acoustic peaks. When experimental uncertainties are reduced, these effects either will help to explain the potential discrepancy or will be ruled out by the CMB measurements.

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There are two broad classes of existing proposals aimed to resolve the above discrepancy. The first approach is to take the high value of $\Omega_B$ as granted by the CMB anisotropy measurements and try to make the predictions of BBN compatible with it. This can be achieved either by relaxing some of the assumptions of the standard BBN scenario (see, e.g., [6]) or assuming reduction of photon entropy between nucleosynthesis and recombination epoch [7]. Another approach is to find a mechanism of suppression of the second acoustic peak. Such mechanism may invoke (see, e.g. [8]), for instance, a tilted spectrum of primordial fluctuations and large reionization optical depth, leading to damping of the features in the CMB spectrum at small angles.

It is important to note that the approach based on the high baryon density ("baryon drag") predicts the suppression of all even peaks relative to the odd ones [2]. Future precise measurements of the third acoustic peak are likely to discriminate between the two approaches.

In this note we discuss a mechanism of the third type which also leads to the suppression of all even acoustic peaks but does not require high baryon density and, as a result, is compatible with the standard BBN scenario. In order to describe our mechanism, let us, following Ref. [2], briefly recall the physics of acoustic oscillations and how the baryon drag works.

When the size of the primordial adiabatic density fluctuation becomes smaller than the horizon scale, its amplitude starts to grow due to the gravitational instability. At the epoch of interest (roughly, between radiation–matter equality and recombination) the primordial matter has two components — photon-baryon-electron plasma and CDM. The pressureless CDM component experiences the gravitational infall providing seeds for the formation of the structure in the Universe, while the density perturbations in the plasma cease to grow and turn into the acoustic oscillations, as the pressure due to the photon component compensates for the gravitational attraction. After recombination, when photons and baryons become non-interacting, baryons fall in the gravitational wells formed by the CDM density fluctuations giving rise to galaxies, while photons propagate freely. Inflation provides equal initial amplitudes for the oscillations at different scales, so the density contrast in the acoustic wave (and, as a result, photon temperature) at recombination is determined by its phase only, which in turn is determined by the ratio of the wavelength of the oscillation to the sound horizon at recombination. This gives rise to the oscillatory structure in the angular spectrum of CMB.

Higher baryon density leads to reduction of pressure in the plasma, that changes the balance between pressure and gravity and shifts the zero point of the oscillations. This results in enhancement of the amplitudes of all odd peaks relative to the even ones. Then it is clear that the same effect could come from any other massive particles ($X$-particles) constituting a fraction of CDM and interacting with the components of the plasma strongly enough to be involved in the acoustic oscillations. Certainly, this condition implies that $X$-particles cannot be responsible for the seeds for the galaxy formation, so they cannot be the only component of the CDM. On the other hand, the difference between values of $\Omega_B h^2$ evaluated from BBN and the CMB measurements is about $\sim (1/2)\Omega_B$. Consequently, the density $\Omega_X$ of the $X$-particles as small as a few percent of the total density is sufficient to make these two predictions compatible with each other, so there is still enough room for the conventional CDM, weakly interacting with the photon-baryon plasma.

In this note we estimate the suitable range of parameters (masses and interactions) of the $X$-particles and discuss existing limits on various candidates.

Let us consider $X$-particles with mass $M_X$, which can scatter elastically off protons with the cross section $\sigma_{Xp}$. The rate of the energy transfer from the photon-baryon plasma to these particles is

$$\frac{dE_X}{dt} = \Delta E_X \tau^{-1} \tag{2}$$

where $\Delta E_X$ is the energy transfer per one collision and $\tau$ is the characteristic time between the collisions. Assuming isotropic scattering one has

$$\Delta E_X = 2\frac{m_p M_X}{(m_p + M_X)^2}(E_p - E_X)\ , \tag{3}$$

where $E_p$ and $E_X$ are kinetic energies of the proton and $X$-particle, respectively. The timescale $\tau$ between two subsequent collisions is

$$\tau = (n_B \sigma_{Xp} \upsilon)^{-1}\ , \tag{4}$$

where $n_B$ is the baryon number density and $\upsilon$ is relative velocity. Protons heat $X$-particles in the collisions. Due to this process $X$-particles may come into kinetic equilibrium with protons with corresponding time scale $t_{eq}$ given by

$$t_{eq}^{-1} = \frac{2}{3T}\frac{dE_x}{dt}\ , \tag{5}$$

where $T$ is the temperature of the plasma. $X$-particles will be involved in the acoustic oscillations at recombination and will suppress the amplitude of the second acoustic peak if the equilibration time $t_{eq}$ does not exceed the inverse expansion rate of the Universe $H_r^{-1}$ at that moment. Combining Eqs. (2)–(5) and expressing the Hubble constant $H_r$ and baryon density $m_p n_B$ through their present values $H_0$ and $\Omega_B \rho_c$ one evaluates the following bound for the cross-section-to-mass ratio of the $X$-particle

$$\frac{\sigma_{Xp} M_X^{1/2}}{(M_X + m_p)^{3/2}} \gtrsim \frac{H_0}{2\Omega_B}\sqrt{\frac{m_p}{3T_r}}\frac{1}{\rho_c}\left(\frac{T_0}{T_r}\right)^{3/2}\ ,$$

where $T_0 = 2.7$ K and $T_r = 0.25$ eV are the present CMB temperature and the temperature at recombination. Taking the standard BBN value $\Omega_B h^2 = 0.02$ one obtains

$$\sigma_{Xp} \gtrsim 2.7h \cdot 10^{-22}\ \frac{(M_X + m_p)^{3/2}}{M_X^{1/2}}\frac{\text{cm}^2}{\text{GeV}}\ . \tag{6}$$

Here $\sigma_{Xp}$ is the cross section corresponding to the relative velocity $\sim 10^{-5}$. Certainly, this lower bound implies extremely large cross sections. In concrete models one can evaluate $\sigma_{Xp}(\upsilon)$ and find the interval of $M_X$ allowed by present experimental data.

As the first example, let us consider the case in which the cross section $\sigma_{Xp}$ is velocity-independent for $\upsilon \sim 10^{-5} \div 10^{-3}$. Then the cross section of $X$ scattering off baryons in halo is also larger than the right hand side of Eq. (6). Surprisingly, as it was emphasized recently [9], even if all CDM species interact equally strongly with ordinary baryonic matter, as large cross section as

$$\sigma_{Xp} = 8 \cdot 10^{-25} \div 1 \cdot 10^{-23}\left(\frac{M_X}{\text{GeV}}\right)\ \text{cm}^2\ . \tag{7}$$

at the relative velocity $\sim 10^{-3}$ cannot be excluded at present if CDM particles are heavier than $\sim 10^5$ GeV or lighter than $\sim 0.5$ GeV. The bound (6) requires an order of magnitude higher cross section for the same mass. However the upper bound in Eq. (7) is not applicable in our case. Indeed this bound comes from the consideration of the heating rate $\gamma$ of non-ionized interstellar clouds by elastic collisions of $X$-particles with Hydrogen [10]. Namely, this limit was obtained by requiring that the heating rate $\gamma$ is smaller than the observed cooling rate $\lambda = (8.1 \pm 4.8) \times 10^{-14}$ eV/s [11]. Upper limit in Eq. (7) assumes that $X$-particles constitute all Dark Matter in the halo. However, as we noted above, as low density of $X$-particles as $\Omega_X h^2 = 0.01$, is sufficient to suppress the amplitude of the second acoustic peak to the observed value. Correspondingly, the heating rate $\gamma$, which is proportional to the density of $X$-particles, is suppressed at the same values of $M_X$ and $\sigma_{Xp}$ by a factor of

$$\Omega_X/\Omega_M \sim 1/15 \div 1/25$$

for $\Omega_M = 0.3 \div 0.5$ . Consequently, the upper bound is weaker, by this factor, as compared to Eq. (7) and does not contradict Eq. (6).

Another upper limit on $\sigma_{Xp}$ close to that in Eq. (7) is related to the halo stability [9] and does not apply to $X$-particles for the same reason — we do not assume that $X$-particles constitute the halos of galaxies, so the fact that they are stopped in the disc does not lead to the instability of the halos.

Finally, it is worth noting that the interval of parameters given by Eq. (7) is interesting also because self-interaction of the CDM particles in this range may resolve the problem of the weakly interacting CDM model, predicting overly dense cores in the centers of galaxies and clusters and an overly large number of galaxies within the Local Group in contradiction with observations [12]. It is intriguing that this interval is not only very close to the parameters of hadronic interactions as was stressed in Ref. [9] but to the bound (6) as well.

To summarize, a relatively small fraction of CDM, consisting of any stable particles with mass $M_X \lesssim 0.5$ GeV (a lower bound depends on the concrete model of the interaction with baryons) or $M_X > 10^5$ GeV which elastically scatter off baryons with the velocity-independent (at $\upsilon \sim 10^{-5} \div 10^{-3}$) cross section $\sigma_{Xp}$, obeying Eq. (6), guarantees the suppression of the second acoustic peak in the anisotropy spectrum of CMB and does not contradict to the present observational limits.

Another natural candidate to consider is the electrically charged massive particles (champs) [13, 14]. First, let us consider particles with unit charge $X^+$ and $X^-$. As was explained in Ref. [13] the fates of these particles in the Early Universe are very different. Positive champs survive unscathed till the epoch of recombination when they capture electrons and form superheavy Hydrogen. Consequently, before recombination they can be involved in the acoustic oscillations. This happens if their equilibration time in plasma is smaller than the inverse expansion rate $H_r^{-1}$ at recombination. The equilibration time for $X^+$ in plasma is given by [13]

$$t_{eq} = \frac{3M_X m_p}{8\sqrt{2\pi} q^2 \alpha^2 n_B \ln\left(3T/q\alpha k_D\right)} \left(\frac{T}{m_p} + \frac{T}{M_X}\right)^{3/2} , \tag{8}$$

where $q = 1$ is the electric charge of $X^+$ and $k_D = (4\pi n_e \alpha/T)^{1/2}$ is the Debye momentum. This time is smaller than the expansion rate of the Universe at recombination provided $M_X < 10^{11}$ GeV. Consequently, these particles could lead to the suppression of the second acoustic peak.

Negative champs can form electromagnetic bound states with proton and nuclei. In fact, as it was argued in Ref. [13], the dominant part of $X^-$ form neutral bound states with proton ("neutrachamps"). The cross section of the elastic scattering of neutrachamps off protons at small relative velocities $v_p \lesssim 10^{-3}$ was estimated in Ref. [13] by making use of the results for the scattering of slow ions off neutral atoms,

$$\sigma_{pX} = 0.36 \frac{\pi^2}{m_p^2 v_p^2} \; . \tag{9}$$

The interval of $M_X$, where inequality (6) is valid, is forbidden by searches for massive particles in isotopes (for recent review and corresponding references see Ref. [15]). So neutrachamps cannot be responsible for the suppression of the second acoustic peak but could form seeds for the galaxies.

Unfortunately, as pointed out in Ref. [16], this scenario is plagued with observational difficulties. Namely, if champs constituted a significant part of the matter in halo, some of the superheavy hydrogen formed by the positive champs would be trapped by the protostellar clouds during the star formation. Neutrachamps are not captured by these clouds, so $X^+$ have no chance to annihilate in the stars and will live there indefinitely. If the evolution of the host star leads to the creation of a neutron star, $X^+$ will form a black hole in the center of the neutron star and will destroy it on timescales much shorter than the life-time of the Universe. This argument rules out champs with masses up to $10^{16}$ GeV constituting a significant fraction of the halo.

One can try to get around this argument in two different ways. First, one can imagine that there exists a pair of nearly degenerate particle species in which the heavier one is charged and the lighter one is neutral. If the lifetime of the charged particle is somewhat larger than the age of the Universe at recombination and the mass difference between charged and neutral particles is small enough so that the late decay of the former does not lead to the strong distortion of the photon background, then such particles can be responsible for the suppression of the second acoustic peak. Certainly any model of this type requires strong fine-tuning.

Unusual modification of this scenario may be realized in models with infinite extra dimensions where our world is localized on a 3-brane in a non-compact multidimensional space [17]-[19]. Namely, as shown in Ref. [20], it is possible that massive (even charged!) particles have a finite probability to escape into extra dimensions. From the point of view of the 4-dimensional observer such "decay" would mean a literal dissapearance of the particle. In Refs. [21, 22] it was shown that this proccess is compatible with the Gauss laws of the general relativity and electrodynamics and leads to the dissapearence of the gravitational (electric) field of the particle in the causal way. As the dissappeance of the particles into extra dimensions is a tunneling process, the corresponding life-time is naturally very large. Its value depends on the particular mechanism of localization, fundamental parameters of the underlying multidimensional theory and mass of the particle. The simplest case is the scalar field localized on the brane by the gravitational field. In this case the decay rate is given by [20]

$$\Gamma = \frac{\pi M}{\Gamma(2+n/2)\Gamma(1+n/2)} \left(\frac{M}{2k}\right)^{2+n} \; , \tag{10}$$

where $M$ is a mass of the particle, $(n+1)$ is the number of extra dimensions (one of them is infinite and $n$ are compact and warped, see Ref. [22]), $k$ is the inverse AdS radius in the bulk. Assuming that this scale is of the order of 4-dimensional Planck mass, $k \sim 10^{19}$ GeV, one has the following value for the ratio of the life-time of the scalar particle $t_s$ to the life-time of the Universe at the recombination $t_r \sim 1.8 \cdot 10^{13}$ sec,

$$t_s/t_r = \frac{5 \cdot 10^{-58}}{\Gamma(2+n/2)\Gamma(1+n/2)} \left(\frac{2 \cdot 10^{19}\ \mathrm{GeV}}{M}\right)^{3+n} \; . \tag{11}$$

It follows from Eq. (11) that for $n = 0$, in order to survive untill the recombination, the scalar particle should have mass smaller than a few GeV which is not allowed by collider searches if the particle is charged[3]. However, for larger values of $n$, a life-time of the particle can be in the interesting range (larger than the age of the Universe at recombination and smaller than about 1 Gyr when first stars were formed, in order to avoid the neutron star argument) without strong fine-tuning of the parameters. For instance, for $n = 1$ the mass of the particle should be in the range

$$20 \text{ TeV} \lesssim M \lesssim 160 \text{ TeV} .$$

Another way to get around the neutron star argument is to consider particles of smaller charge. Fluxes of the particles of charges $q \gtrsim 0.1$ are strongly limited by direct searches [23], so one has to consider particles with smaller charges, $q \lesssim 0.1$. Let us check that particles with so small electric charges can give rise to the suppression of the second acoustic peak. Comparing equilibration time (8) for $X$-particle of charge $q$ with the inverse expansion rate of the Universe at recombination one obtains that the $X$-particle mass should be less than

$$M_X < 3.4 \cdot 10^9 q^2 (18.6 - \ln q) \text{ GeV} \tag{12}$$

for $M_X > m_p$, and larger than

$$M_X > 7.3 \cdot 10^{-20} q^{-4} (18.6 - \ln q)^{-2} \text{ GeV} \tag{13}$$

for $M_X < m_p$, in order that $X$-particles have been involved in the acoustic oscillations. In Fig. 1 we present this bound (dash-dotted line) in the exclusion plot for the parameters of models with millicharged particles and without paraphotons (see Ref. [24]). There exists allowed region of parameters where millicharged particles are involved in the acosutic oscillations. Dark grey area corresponds to the region of allowed parameter space where masses of millicharged particles satisfy Eq. (12) and their relic density is higher than $\Omega_{mc}h^2 = 0.01$. The CMB result (1) implies that this region of parameter space is excluded (assuming inflationary spectrum with $r = 0$ and baryon density favored by the standard BBN). In particular we practically close the window for light millicharged particles with charges $10^{-5} \div 10^{-3}$. Millicharged particles of masses and charges belonging to the thick solid line in Fig. 1 may be responsible for the observed suppression of the second acoustic peak.

In models with paraphotons the CMB result (1) implies that region with $q \sim 10^{-4} \div 10^{-1}$ and $M_X \sim$ *a few* TeV is excluded (assuming inflationary spectrum with $r = 0$ and baryon density as in the standard BBN scenario). Millicharged particles with $M_X \approx 1$ TeV and $q \approx 10^{-4} \div 10^{-1}$ may be responsible for the observed suppression of the second acoustic peak.

To conclude, the observed suppression of the second acoustic peak in the CMB anisotropy may be due to the interaction of the primordial photon-baryon plasma with $X$ particles constituting a fraction of the CDM of order a few percent. In the case of elastic velocity-independent scattering (in the velocity interval $v \sim 10^{-5} \div 10^{-3}$) the required cross sections (6) are extremely large, but intriguingly similar to the recently predicted range (7) for the self-interaction of the CDM. In this case the direct searches for Dark Matter restrict $X$-particles to be within mass interval $\sim 0.1 \div 0.5$ GeV or to be heavier than $10^5$ GeV. Another candidate which may be responsible for the suppression of the second acoustic peak emerges in multidimensional scenarios with non-compact extra dimensions. It is a charged particle, stable in the multidimensional theory, which may escape from our brane through tunneling into extra dimensions. Yet another

[3]It is worth noting also that in the simple model which we consider gauge fields are gravitationaly localized on the brane only at $n > 0$ [22].

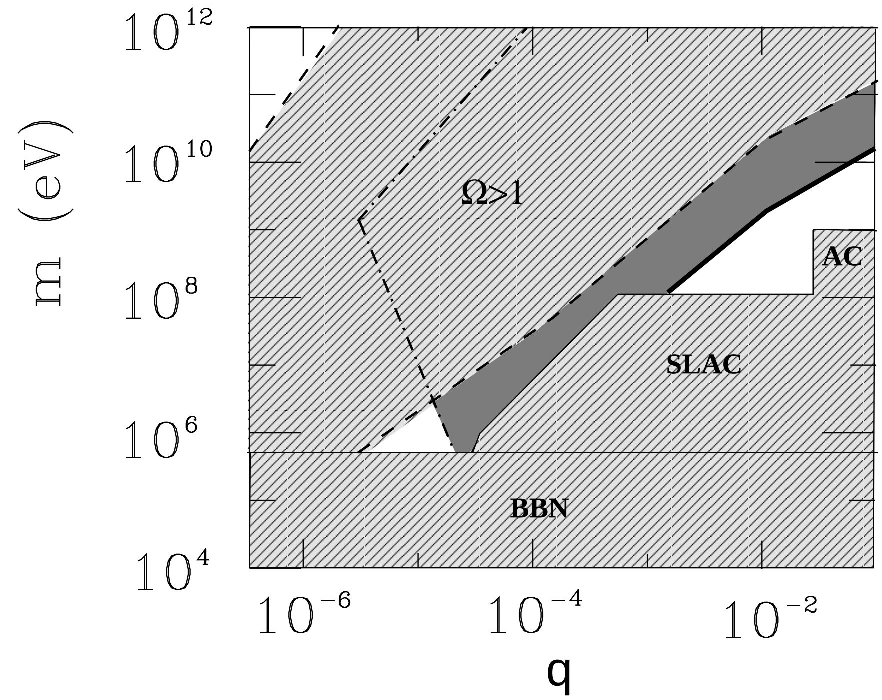


Figure 1: An exclusion plot in the mass-charge space for millicharged particles in models without paraphotons. Dashed lines correspond to the relic density of millicharged particles equal to $\Omega_X h^2 = 1$. To the right of dash-dotted line millicharged particles are involved in the acoustic oscillations. Light grey shaded area is experimentally excluded. Models with fractional charge $q \gtrsim 0.1$ are ruled out by strong limits on fluxes of the millicharged particles. Dark grey area is excluded, if millicharged particles do not contribute to the oscillatory structure of angular CMB spectrum. Thick solid line corresponds to models explaining the absence of second acoustic peak.

possibility is the existance of millicharged particles with the electric charge ranging from $\sim 10^{-4}$ to $\sim 10^{-1}$ and with mass $M_X \sim 0.1$ GeV $\div$ 1 TeV.

The authors are indebted to V.A. Kuzmin, V.A. Rubakov, D.V. Semikoz, M.E. Shaposhnikov, P.G. Tinyakov and I.I. Tkachev for helpful discussions. SD thanks Institute of Theoretical Physics, University of Lausanne, where this work was completed, for hospitality. This work was supported in part by RFBR grant 99-01-18410, by the Council for Presidential Grants and State Support of Leading Scientific Schools, grant 00-15-96626, by CRDF grant (award RP1-2103) and by Swiss Science Foundation grant 7SUPJ062239.

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